

# Nanofabricated SNS Junction Series Arrays in Superconductor-Normal Metal Bilayers

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**Abstract**—We have applied our existing focused ion beam-based planar SNS bridge junction technology to the fabrication of series arrays. Individual junctions are created in a micron-width bilayer track (125 nm Nb on 75 nm Cu) by milling a 50 nm wide trench in the upper superconducting layer. The characteristics of 10 junction series arrays at junction spacings 0.2  $\mu\text{m}$ –1.6  $\mu\text{m}$  have been studied at 4.2 K and above. Measurements of differential resistance versus current reveal the distribution of individual junction critical currents within the array. Spreads of under 20% of the mean critical current are typically observed. Locking of all the junctions in the array under applied microwaves is observed as the transition temperature is approached. This effect is achieved at a lower temperature for shorter junction spacings, suggesting a penetration depth dependent electromagnetic coupling mechanism.

## I. INTRODUCTION

We have developed a reliable and versatile technique for fabricating SNS junctions in superconductor normal metal bilayers using a focused ion beam microscope [1,2]. A micron-width track is defined in the bilayer. A 50 nm wide trench is milled in the upper superconducting layer to achieve weak coupling. We are able to determine the depth of the trench by an *in situ* resistance measurement technique [2,3]. By carefully selecting the thicknesses of the superconducting and normal metal layers (125 nm Nb on 75 nm Cu) junctions with non-hysteretic RSJ-like current-voltage characteristics, critical current ( $I_C$ )  $\sim 1\text{mA}$  per  $\mu\text{m}$  track width and characteristic voltage ( $I_C R_N$ )  $\sim 50\text{ }\mu\text{V}$  at 4.2 K can be obtained over a range of milling depths. A key feature is that at 4.2 K the majority of the Josephson current transport is through the remaining Nb in the bottom of the trench; the Cu layer acts as a resistance shunt and heat sink. [2] These characteristics, combined with a very high potential integration density, make these devices excellent prospective candidates for lumped array applications.

## II. DEVICE FABRICATION

A 125 nm Nb 75 nm Cu bilayer is deposited on an oxidized Si substrate in an ultra-high vacuum magnetron sputtering system in sequence without breaking vacuum.

This ensures excellent film and interface quality. A main track containing sections of width 3-8 microns intersected by voltage taps is defined in the bilayer by photolithography and reactive ion etching. The patterned sample is wirebonded to a holder in a four-point resistance measurement configuration and the sample is transferred to a standard FIB for device fabrication. A 1  $\mu\text{m}$  width region of track is defined by milling on a high beam current (11 pA). Then an array of junctions is milled using a 4 pA beam either in series (milling each junction sequence) or in parallel (milling the array as a single object). For comparison a single junction is milled in a neighboring section of track. This whole process is performed without altering the beam focus. The milling depth can be deduced from an *in situ* resistance measurement. Customized software allows us to halt milling when the desired change in resistance and hence milling depth is reached. For this study arrays of 10 junctions of spacings 0.2  $\mu\text{m}$ –1.6  $\mu\text{m}$  were milled in parallel along the main track of a single 10 mmx10 mm chip. The milling time per junction (area milled 2  $\mu\text{m}$  x 50 nm) was 11 s.

## III. RESULTS

Basic device characterization was performed between 4.2K and the transition temperature ( $T_C$ ) using a dip probe including magnetic field coils and microwave antenna. Current-Voltage ( $I$ - $V$ ) characteristics were obtained in a quasi-static current-biased measurement. Microwave measurements were possible in the range 11-18 GHz.

An example of phase locking as evidenced by a x10 Shapiro step is shown in Fig. 1 (10 junction array, 1.6  $\mu\text{m}$  spacing, 14.0 GHz, 6.0 K – step appears at 0.28 mV). Table I shows parameters for arrays of spacing 0.2-1.6  $\mu\text{m}$ . The locking temperature given is the lowest at which a convincing x10 step was observed. In general this temperature is lower when the junction spacing is shorter, suggesting a penetration depth-dependent electromagnetic coupling mechanism.

Low noise differential resistance measurements as a function of bias current ( $dV(I)/dI$ ) were made with the aid of a lock-in amplifier. This allowed the switching of individual junctions in an array to be observed. Fig. 2 shows the  $dV(I)/dI$  characteristic of an array and a single junction at 4.2K. From the deduced  $I_C$  distribution (statistics shown in Table I), the  $I$ - $V$  of a single junction array can be convincingly reconstructed. Significantly this best fit is obtained by scaling the  $I$ - $V$  characteristic of a single junction assuming constant  $R_N$  (rather than  $I_C R_N$ ). In these devices, when the milled trench does not penetrate the Cu layer,  $R_N$  is effectively constant (Cu has a resistivity a factor of 10 lower

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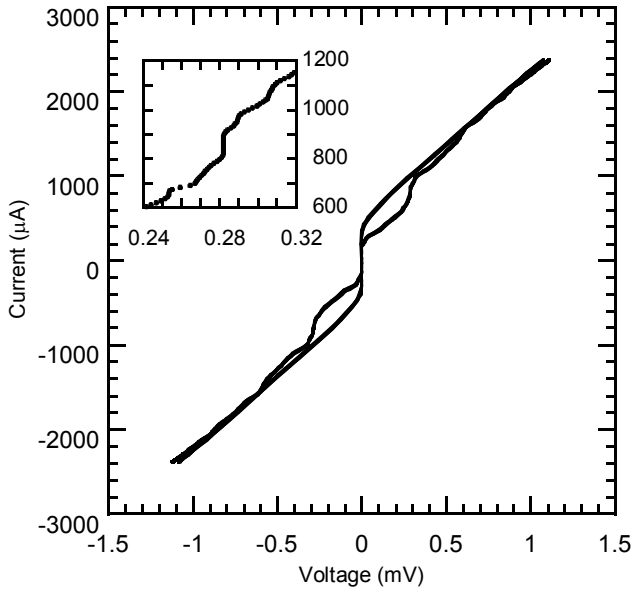


Figure 1: 10JJ array (spacing 1.6  $\mu\text{m}$ ) at 6.0 K exhibiting a nearly flat Shapiro step (14.0 GHz). Inset: Low-noise measurement of x10 step exhibiting non-ideal features.

than Nb in the normal state). This means that for such an array the spread in  $I_C$  (not  $I_C R_N$ ) is crucial. (In arrays using high temperature superconductors, a normal metal shunt layer has been employed to achieve exactly this result [5]).

A low-noise measurement of an array under microwave irradiation reveals structure in addition to the Shapiro-like step (see Fig. 1 inset). This may arise due to the non-ideal individual junction microwave response. The single junction differential resistance profile shown in Fig. 2 is clearly not RSJ-like, with a bump at  $\sim 1.5 \times I_C$  (common in SNS junctions with long diffusive barriers [6]). Furthermore, such junctions display fractional Shapiro steps under microwave irradiation.

TABLE I

STATISTICS FOR ARRAYS OF SPACINGS 0.2 TO 1.6  $\mu\text{m}$  AT 4.2 K

Spacing ( $\mu\text{m}$ )	$I_C$ ( $\mu\text{A}$ )		Spread (Standard Dev./Mean) (%)	Locking Temperature (K)
	Min.	Max.		
0.2	890	1700	19.8	4.2
0.4	2140	3000	10.7	5.0
0.6	510	1410	36.2	—
0.8	980	1510	11.8	5.0
1.6	1290	1970	12.3	5.5

The beam was refocused for the milling of each array, so although the current, area, and milling time per junction were equal, the focussing conditions are only identical for junctions within that particular array.

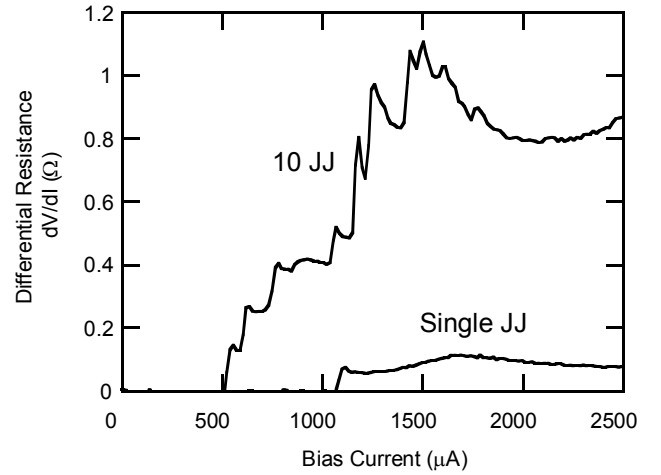


Figure 2: Differential resistance measurement for a 10 junction array (0.6  $\mu\text{m}$  spacing) and a single junction (below) at 4.2 K.

#### IV. DISCUSSION

The addition of a superconducting ground plane may lead to improved locking, as the spread in  $I_C$  may arise due to an inhomogeneous current distribution in the array. Utilizing the coplanar waveguide which already exists on our mask design should improve microwave coupling into the array. For the writing of arrays of large numbers of junctions of sufficient uniformity an indirect method of patterning (anisotropic etch with a mask and etch stop layer) may be required.

#### V. CONCLUSION

We have applied our existing junction technology to the fabrication of series arrays. At 4.2 K the spread in  $I_C$  is in the range 10-36 %.  $R_N$  is determined by the shunting Cu layer thickness. Locking behavior is observed at elevated temperatures. For arrays of comparable  $I_C$  spreads the temperature at which locking first occurs is lower when the junction spacing is shorter, suggesting a penetration depth-dependent electromagnetic coupling mechanism.

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